

9th International Conference on Sustainability in Energy and Buildings, SEB-17, 5-7 July 2017,
Chania, Crete, Greece

Thermal comfort in the historical urban canyon: the effect of innovative materials

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Abstract

Urban heat island (UHI) can considerably affect the thermal quality of the urban environment, especially within urban canyons, that have typically low sky view factor and limited surface heat re-emission capability. A huge research effort has been registered to develop mitigation solutions for UHI, such as cool materials and greenery. Nevertheless, it is not always possible to apply such strategies in historical urban environments due to constraints for the preservation of their cultural value that do not allow to modify the exterior architectural appearance of heritage buildings.

In this scenario, the present paper deals with the analysis of the potential of innovative cool materials characterized by the same appearance of historical ones in mitigating the UHI occurring in the context of a historical urban canyon located in central Italy selected as pilot case study. To this purpose, a preliminary experimental characterization of such innovative highly reflective materials has been performed. Afterwards, an experimental continuous monitoring campaign of the main outdoor microclimate parameters and a numerical modelling of the canyon have been carried out to evaluate the local mitigation capability of such materials when applied over the vertical and horizontal surfaces of the historical canyon.

The results show the huge potential of the proposed innovative cool materials in mitigating the local microclimate of the historical urban canyon. In fact, a MOCI reduction up to 0.15 and 0.30 is detected by applying cool red envelope materials and cool red envelope materials plus cool grey paving materials, respectively, on the canyon surfaces.

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Peer-review under responsibility of KES International.

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Keywords: Urban heat island; cool materials; continuous monitoring; microclimate simulation; historical urban canyon

1. Introduction and Purpose of the work

Buildings are responsible for more than 40% of the world global energy consumption [1-2]. Such percentage is expected to increase in the future due to the climate change phenomena threatening urban environments and human health [3]. For these reasons, the need for innovative solutions for sustainable urban design has become undeniable, also due to the requirements of the EU Horizon 2020 directives [4]. A significant research effort has been dedicated to the investigation of Urban Heat Island [5], by developing tailored mitigation strategies to reduce its intensity. The urban heat island effect on buildings cooling energy demand was evaluated in [6] for a small Mediterranean city. An extensive statistical analysis revealed strong UHI intensity reaching values up to 6°C with a mean intensity of 3.8°C in summer. To the same aim, the patterns of urban heat island phenomenon were analyzed in the Shanghai area by means of an integrated GIS/RS-based approach [7]. Results showed that with the rapid expansion of the urbanized landscapes, the heating effect of impervious surfaces proportionally increased. Among the currently available urban heat island mitigation techniques, the increase of highly-reflective “cool” surfaces and green spaces are identified as the most effective in reducing (i) built surfaces overheating, (ii) building cooling energy consumption, and (iii) CO₂ emissions in the atmosphere [8-9]. The urban heat island phenomenon was demonstrated to be particularly exacerbated in urban street canyons, i.e. canyon-like streets in urban areas. Santamouris et al. [10] analyzed the variation of the surfaces and air temperature distribution inside a canyon in Athens. A temperature difference up to 19°C was detected under hot weather conditions between the two opposite facades. Moreover, an air temperature stratification up to 33°C was detected during the day. Similarly, Andreou et al. [11-12] performed a thermal comfort analysis to investigate the degree of influence of different parameters, i.e. street geometry, orientation, wind speed, surface albedo, and trees presence, on thermal comfort conditions in urban canyon. It was demonstrated that the outdoor comfort in the canyon is mainly affected by exposure to solar radiation and, therefore, street orientation and height/width ratio (H/W) have a considerable effect. Over the years, several research studies were performed also to monitor pollutant dispersion and air quality in urban street canyons as non-negligible components affecting pedestrian comfort and overall microclimate conditions [13-14]. Moreover, the use of numerical simulation tools to evaluate local microclimate has highly increased [15-16]. Building upon previous studies, the present paper investigates the local microclimate conditions of a historical urban canyon in central Italy, and aims at bridging the gap between studies about local microclimate of urban canyons and the ones investigating the impact of innovative solutions for improving local outdoor comfort conditions in historical urban canyons, where typical retrofit solutions cannot be applied due to the preservation constraints. Therefore, the need to take into account the constraints of preserved historical urban areas, that usually cannot be modified, is here taken into account. To this purpose, the impact of innovative cool materials on the urban canyon horizontal and vertical surrounding built surfaces is evaluated. Such innovative materials are highly infrared reflective stone and cement-based materials suitable for implementation in historical urban areas, where the architectural appearance of the buildings cannot be modified for preservation regulations. After the experimental analysis of the materials main thermal-optical properties, a numerical analysis is carried out to simulate their microclimate effect generated in the historical urban canyon selected as case study. Moreover, a continuous monitoring campaign is carried out for the experimental validation of the numerical model. Therefore, the final aim of the study is to evaluate the impact of the experimentally tested innovative cool materials in a historical urban canyon to assess the thermal benefits generated in terms of pedestrians’ outdoor comfort.

2. Materials and method

The research was carried out by means of coupled experimental and numerical analysis. On site monitoring was performed in order to validate the simulation performed with ENVI-met software. These steps are more in depth described in the following sub-sections.

2.1. Development and experimental characterization of the innovative cool materials

Cool materials constitute a widely employed passive solution to reduce energy consumption and mitigate urban heat island [17–18]. Such materials are applied into the built environment both as roof, paving or building envelope elements, also considering their durability [19]19–22]. They are usually light-colored, but still a variety of colored cool materials were developed in the last years by researchers, by employing infra-red reflecting pigments (IR pigments) [23], [24]. Proposed solutions consisted in paints, aluminum elements, asphalt shingles, cool colored concrete tiles. In order to blend in with the historical built environment colors and appearance, cool colored cement-based mortars were developed for the purpose of this study. The peculiarity of such materials is the possibility to decide the exact color saturation directly on site, by mixing the IR pigment, which is almost white in color, and the selected colored pigment (e.g. red or gray). This would permit to buy just two pigments and mix them on site to match the color of the historical envelope. Prototypes were implemented by considering the most common colors of the historical cities of central Italy, which are red and gray. The prototype mix was composed by white Portland cement (37% by weight), fine glass aggregates (41%), water (12%), traditional colored pigments (5%) and IR pigments (5%) (Fig. 1).

In order to insert thermal-optic characteristics into the dynamic simulation, prototypes were in lab analyzed. Solar reflectance (SR) was assessed by means of spectrophotometer, in accordance with current regulation [25], while thermal emissivity was measured with a portable emissometer, following ASTM C1371 [26].

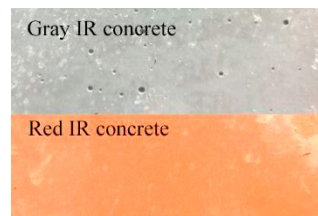


Fig. 1. Cool prototypes developed for the historical built environment.

2.2. Monitoring setup

An in-field experimental monitoring campaign was carried out in the canyon to collect the main outdoor microclimate parameters during spring. All the parameters were continuously monitored every 10 minutes from 9:00 a.m. until 7:00 p.m. Such experimental data were used for the validation of the elaborated numerical model. The monitoring equipment consisted of a Wireless Sensor Network station composed by one node, connected to the different sensors via cable, and a data gathering gateway. Moreover, three waterproof Tinytag data logger with a built-in probe were used for air temperature and relative humidity measurement. The technical characteristics of all sensors used for the continuous monitoring are reported in Table 1. The monitoring station was positioned as close as possible to the center of the street. The positioning the sensors is listed as follows:

- Air temperature and relative humidity probe in the centre of the canyon at about 1.5 m height [°C; %];
- Air temperature and relative humidity probe close to the South-East oriented side of the canyon at about 1.2 m height [°C; %];
- Anemometer for the wind speed in the canyon at about 1.5 m height [m/s];
- Surface temperature of the street floor [°C];
- Air temperature and relative humidity probe close to the North-West oriented side of the canyon at about 1.2 m height [°C; %].

By means of the collected local microclimate parameters it was possible to determine the corresponding values of the mean radiant temperature by using the MEMI and MENEX models [27]–[28].

Table 1. Technical characteristics of the sensors.

Sensor	Type	Dimensions [mm]	Measurement range	Working range	Cable length [m]	Accuracy
AIR TEMPERATURE AND RELATIVE HUMIDITY PROBE	10K NTC Thermistor and Capacitive	50x50x30	T: -25÷85 °C RH: 0÷100 %	-25÷85 °C	-	0.4÷0.8 °C (-25÷85 °C) ±3.0 % @ 25 °C
SURFACE TEMPERATURE PROBE	PT100 1/10 DIN 4 wires	20x20	-40÷200 °C	-40÷200 °C	3	< 0.1 °C (-20÷100 °C)
WIND SPEED SENSOR	Anemometer	40x300 125 (Ø)	0÷50 m/s	-10÷70 °C	10	< 0.1 m/s (0.4÷30 m/s), < ±1% (> 30 m/s)

2.3. Numerical analysis of the outdoor thermal comfort

The different simulated urban canyon scenarios were compared in terms of outdoor thermal comfort conditions by calculating the MOCI [29]-[30] index. The MOCI is an empirical index developed to evaluate the thermal perception of people in the Mediterranean area. It was implemented starting from the results of the surveys elaborated according to the ISO 10551 [32]. 941 people were asked to define their thermal sensation among the ASHRAE 7-point scale (cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2) and hot (+3)). Moreover, they were asked to reply to additional questions about personal data such as age, gender, clothes, activity performed just before the questionnaire, exposure time to the investigated environment. Simultaneously to the survey, a dedicated measurement campaign was carried out to collect data about dry bulb temperature, relative humidity, air velocity, global radiation. This allowed to correlate the vote of the interviewees to both the (i) environmental and (ii) operative variables. The age and the global irradiation variables were finally excluded after the evaluation of the VIF (i.e. Variance Inflationary Factor) and consistency [30]. Therefore, a Best Subsets Analysis showed that by comparing 127 different available regressions model by mean of the corrected R^2 and the C_p statistic, the following equation was generated (Eq.1):

$$MOCI = -4.068 - 0.272 \cdot WS + 0.005 \cdot RH + 0.083 \cdot T_{MR} + 0.058 \cdot T_A + 0.264 \cdot I_{GL} \quad (1)$$

The assessment was carried out by means of ENVI-met software **Errore. L'origine riferimento non è stata trovata.**3], after validating the model with the monitoring campaign. Moreover, the size of the cells composing the model was evaluated by comparing three different cell dimensions, to achieve a balance between computational time and minimum error. Finally, the importance of adopting a microclimate evaluation that is focused on specific population needs has to be highlighted. To this aim, obtained results were also analyzed in terms of Actual Sensation Vote (Eq. 2) [34] and Thermal Sensation Perception (Eq. 3) [35]:

$$ASV = -8.527 - 0.457 \cdot WS + 0.013 \cdot RH + 0.059 \cdot T_{MR} + 0.245 \cdot T_A \quad (2)$$

$$TSP = -3.557 - 0.304 \cdot WS + 0.0105 \cdot RH + 0.0677 \cdot T_{MR} + 0.0632 \cdot T_A \quad (3)$$

The actual Sensation Vote was obtained in Guangzhou (China), while Thermal Sensation Perception characterizes thermal perception of Sao Paulo (Brazil) population. These two indices were selected since they are based, as MOCI does, on ASHRAE 7 points scale, so a comparison is more easily performed.

3. Description of the pilot case study

The criteria for selecting a representative urban canyon were (i) the H/W ratio, according to the historical Mediterranean ones, (ii) the sufficient length of the canyon in order not to have other variables influencing the assessment, (iii) the location in a historical urban area, and (iv) the possibility to perform the monitoring without being affected by traffic. Therefore, Via delle Carrozze (Rome, Italy), which complied with all these requirements, was selected as case study urban canyon (Fig.2).



Fig. 2. Via delle Carrozze (red line, while Via del Corso is the grey line), views from Google Maps.

The ratio between height and width (H/W) is 3.5, with an almost uniform height equal to 18 m, and width equal to 5 m. Paving material is composed by grey sanpietrini, a traditional paving composed by small block of basalt stone from the region around Rome.

The buildings in this area have a travertine-light stone basement and are covered with reddish ochre mortar.

The selected urban canyon is North-east/South-west oriented and is composed by four blocks of buildings around sixty-five up to seventy meters wide.

In order to investigate the impact of different materials on the local microclimate, three different configurations of the canyon were evaluated and compared: Case 0, representing the current situation; Case 1, with red cool materials applied on the envelope; and Case 2, where both the red cool envelope and a grey paving are applied on the canyon surfaces.

4. Description of the Results

4.1. Materials properties

The tests carried out by means of spectrophotometer showed that red IR mortar has a SR equal to 40%, while the gray has a SR equal to 30% (Table 1). By considering the thermal characteristics, both the prototypes showed the same value, i.e. 0.90, with respect to thermal emissivity, showing that the characteristic does not vary when varying pigments' color. When comparing IR solutions with traditional ones, i.e., stone paving and red traditional, same color mortar, the solar reflectance varies and the materials are thus cooler, while still having the same appearance. On the other hand, the thermal emissivity remains 0.90 (Table 1). Therefore, the impact on thermal comfort is due to the variation in solar reflectance.

Table 1. Solar reflectance measured on 300-2500 nm of cool coloured prototypes, as measured in lab.

Material	Solar Reflectance	Difference with traditional prototypes, same color	Thermal Emissivity	Difference with traditional prototypes, same color
Red IR mortar	40%	+10%	0.90	0.00
Gray IR mortar	30%	+15%	0.90	0.00

4.2. Numerical analysis of the outdoor thermal comfort in the historical canyon

The analysis of microclimate and outdoor thermal comfort in the urban canyon was carried out within the ENVI-met environment during a typical summer day. The reference case is Case 0, which represents the current situation of the urban canyon. The main assumption is to have a constant anthropogenic heat flux, since the focus is to concentrate exclusively on materials-driven variations. Figure 4 shows the MOCI Index map for the urban canyon midpoint at 1.1 m, representing a standing pedestrian's center of gravity.

The configuration leading to more comfortable microclimate conditions is Case 2, where the paving material is gray IR prototype and the envelope material consists of IR red mortar. The plots show that both Case 1 and Case 2 allow to achieve a better local microclimate condition compared to Case 0.

In both cases, red optimized mortar covers the buildings envelope, while traditional stone paving and gray optimized mortar characterize the Case 1 and Case 2 configurations, respectively. The surface albedo is equal to 0.20 and 0.30 for traditional stone paving albedo value and gray optimized mortar, respectively.

During the midday hours, Case 1 generates a MOCI index reduction by 0.15 units, while in Case 2 a decrease of the MOCI up to 0.30 is detected with respect to Case 0, therefore closest to the 0 representing the neutral value.

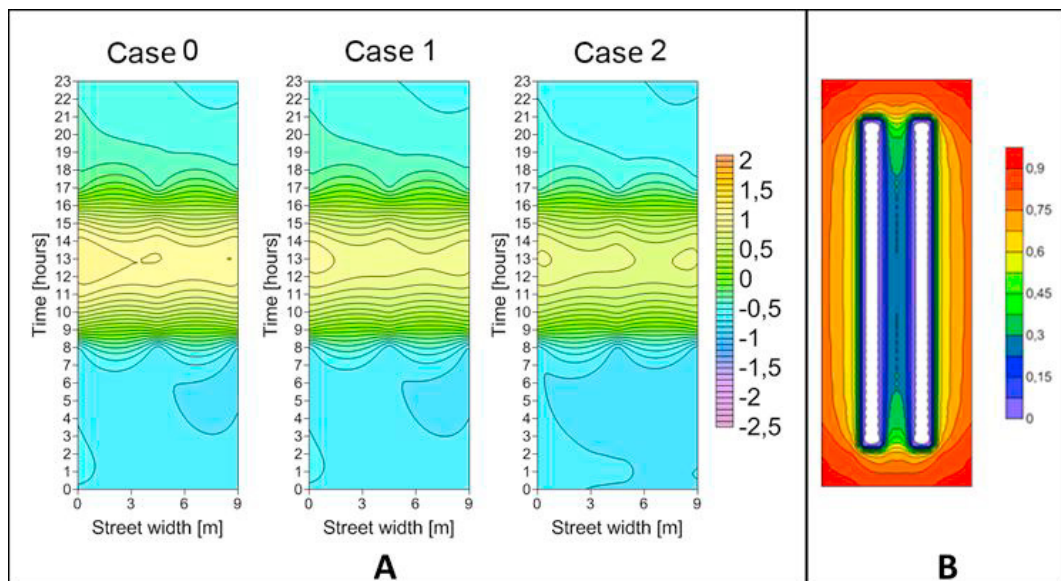


Fig. 3. A) Mediterranean Outdoor Comfort Index (MOCI) hourly values, measured in the canyon midpoint, at 1.1 m on the ground level; B) Ground surface sky view factor for the considered site.

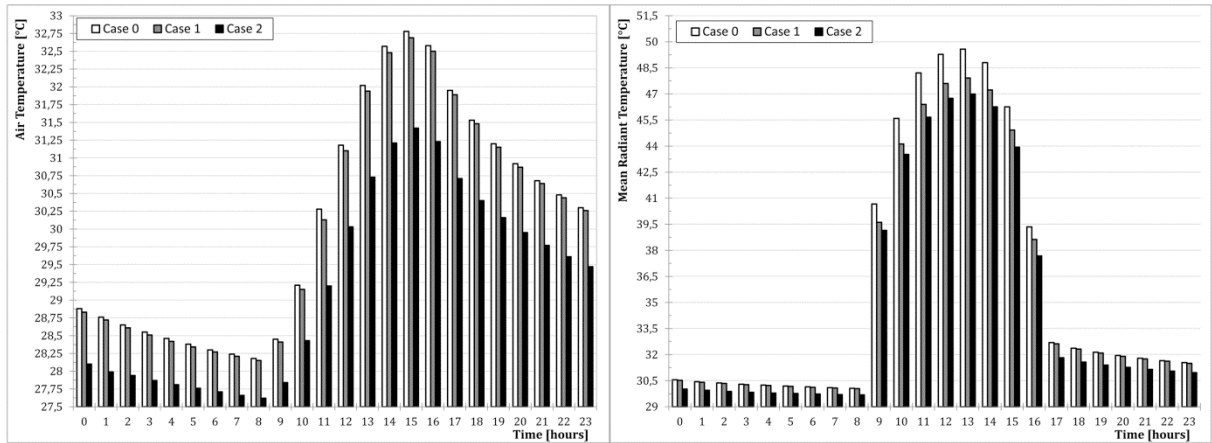


Fig. 4. Trends over time of the air temperature and mean radiant temperature in the difference urban canyon configurations.

The influence of such variables on microclimate and pedestrians' thermal perception is confirmed by the mean radiant temperature coefficient (0.083) from the MOCI equation (Eq. 1). The above-mentioned coefficient represents the inclination of MOCI with respect to mean radiant temperature when all the other variables are considered constant. The MOCI equation (Eq. 1) shows that air temperature coefficient is 0.058. Therefore, the influence of mean radiant and air temperature is confirmed by partial F-test values [30] carried out during their field survey campaign in Rome. During their investigation, the obtained value for mean radiant temperature was 82.4, 14.6 for air temperature, while the relative humidity associated value was as low as 1.4. These findings are confirmed by other researches [36–38], which highlighted how mean radiant temperature is the variable with the highest impact on human body. It is worth noting that these results are a direct consequence of Rome climate, which is not windy, whereas in areas characterized by high wind velocity air temperature is the dominant variable, since it is strictly connected to convective thermal exchanges. All the considerations about Cases and corresponding MOCI are synthesized in Table 2. All the variations of mean and maximum MOCI values with respect to Case 0 are reported for each configuration.

Table 2. Variations of mean and maximum MOCI values with respect to Case 0, the current urban canyon configuration, are reported.

	Mean values difference with respect to Case 0	Maximum values difference with respect to Case 0
Case 1	-0,08	-0,15
Case 2	-0,18	-0,28

5. Discussion

The above-described results confirmed how the variation of materials solar reflectance can have a considerable impact on pedestrians' outdoor thermal comfort conditions in urban canyons. In this scenario, reference values were found for similar applications in the built environment. Measurements carried out in field are provided for instance in Gaitani et al. [39], who demonstrated how cool pavement tiles (68% solar reflectance) and cool asphalt (50% solar reflectance) were able to lower surface temperature of an entire major open area in Athens. The application of the such materials replacing traditional ones led indeed to a reduction of surface temperatures up to 10°C. Such solutions, together with urban greenery and earth to air heat exchangers, were able to lower local temperature up to 28°C during summer. Also Synnefa and colleagues [40] studied cool but still colored coatings for the built environment, assessing surface temperatures reductions due to solar reflectance values increase, as a consequence of infrared pigments addition. Additionally, the microclimate numerical analysis showed MOCI reduction up to 0.15 and 0.30 due to the implementation of cool red and cool-red envelope materials combined with cool-grey paving materials on the urban canyon surfaces. In Fig. 5, a comparison among MOCI, Actual Sensation Vote, and Thermal

Sensation Perception is carried out. It was observed that in the warmest hours of the day, highest thermal stress is reported by means of Thermal Sensation Perception from analyses in Sao Paulo (Brazil) [35], which is characterized by a mean temperature equal to 21.5 °C during the warmest month of the year. Such value is lower than temperatures assessed in Guangzhou (China) [34] and Rome (Italy) [31] (28.8 °C and 24.4 °C, respectively). This assessment leads to suppose a lower adaptation of Sao Paulo (Brazil) population towards extreme hot conditions. On the other side, during the coldest hours of the early morning, the higher thermal stress was assessed in Guangzhou (China), where the mean annual temperature is higher (22.2 °C). Therefore, the above-mentioned considerations underline the need to tailor specific outdoor areas design based on the sensations and needs of the population living in that specific area.

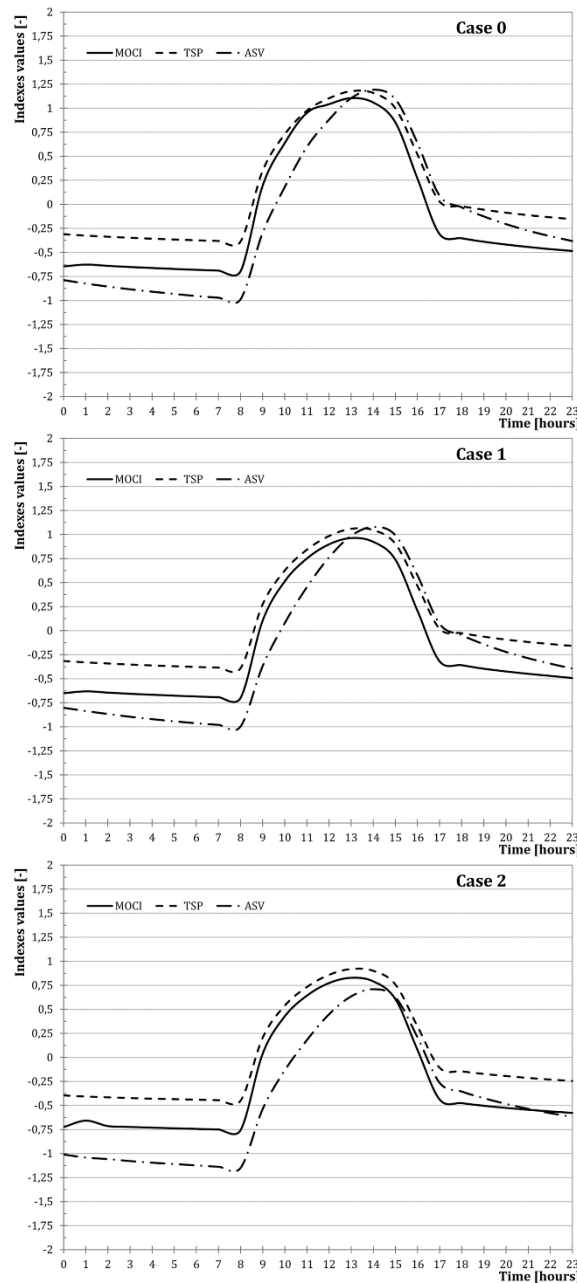


Fig. 5. Trends over time of MOCI, Actual Sensation Vote and Thermal Sensation Perception.

Therefore, the present work demonstrates that it is possible to mitigate local microclimate conditions inside historical urban canyons where typical retrofit solutions cannot be applied due to the local architectural preservation constraints. The solution is represented by the application of such innovative materials tailored to be applied over historical surfaces but characterized by optimized thermal-optical properties able to lower air and surface temperatures inside the canyon.

6. Conclusions

In this paper, a combined experimental and numerical approach is applied to investigate the impact of innovative cool materials on the local microclimate in a historical urban canyon. Such materials, characterized by high solar reflectance capability and thermal emittance, have been developed for application in historical urban areas where it is difficult to apply mitigation strategies due to the preservation constraints imposed by local regulation that do not allow to modify the architecture of the buildings. Therefore, the proposed materials are characterized by the same exterior appearance of the historical ones but have better thermal-optical properties. A preliminary experimental laboratory campaign is carried out to confirm the promising thermal-optical characteristics of the cool materials implemented, consisting of IR reflective red-colored and grey-colored concretes. Therefore, a numerical analysis is carried out to predict the effect of the application of such materials on a case study urban historical canyon in central Italy. The results confirm the thermal benefits generated by the application of the proposed materials over the horizontal and vertical surfaces of the canyon in terms of outdoor thermal comfort for pedestrians. A MOCI reduction up to 0.15 and 0.30 is detected by applying cool-red envelope materials and cool-red envelope materials plus cool-grey paving materials, respectively, on the canyon surfaces. An overall non-negligible mitigation of the local microclimate in the canyon, typically characterized by low sky view factor and exacerbated overheating phenomena, is detected. The present study demonstrates that the proposed highly-reflective materials with the same architectural quality of historic materials could represent a suitable strategy for improving the outdoor environmental quality of heritage urban canyons that usually present uncomfortable thermal conditions in peak summer times for pedestrians due to the low capability of the surfaces to re-emit the incoming radiation out of the urban canopy. Finally, the need to design outdoor areas based on specific population adaptation is underlined.

Acknowledgements

The research leading to this review has been supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 678407 (ZERO-PLUS) and No. 700395 (HERACLES). Dr. Pisello's acknowledgments are also due to the "CIRIAF program for UNESCO" in the framework of the UNESCO Chair "Water Resources Management and Culture" for supporting her research.

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